Military Applications and Research of Miniature Robotics

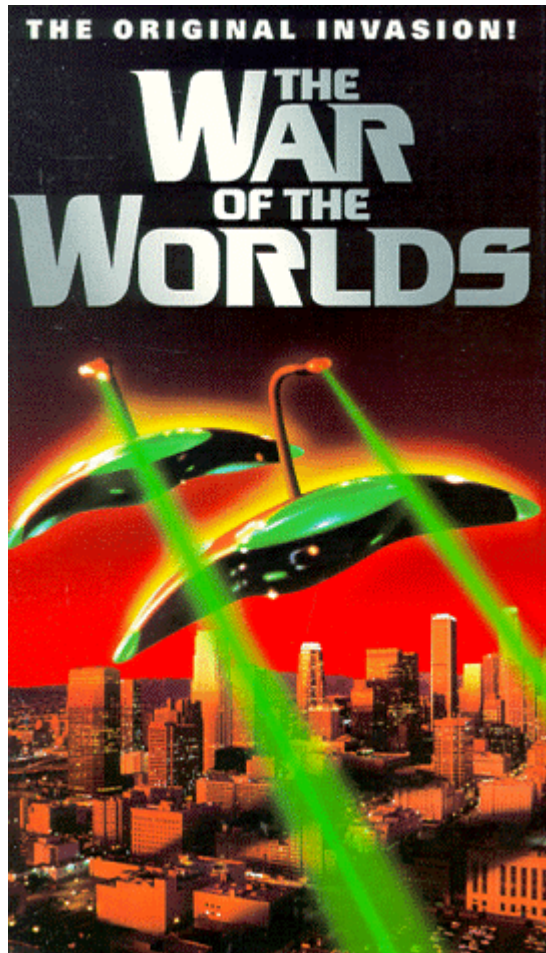## Steve Suddarth

AFMC/CCX

Wright-Patterson AFB OH 45433

(937) 257-6897

steven.suddarth2@wpafb.af.mil

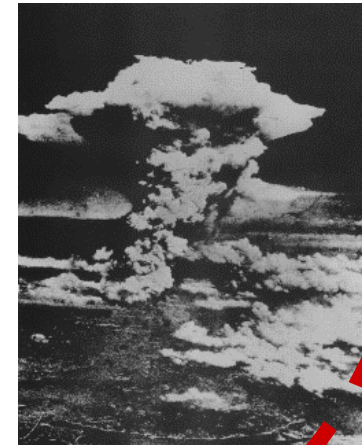# Military Science and Mars Exploration Go Together

Firepower, Mass Increased to the Level of Irrelevance

- Once critical
- Nuclear weapons
  - Too indiscriminate
  - Leads to uncertain peace
- Research now focused on <u>smaller</u> nuclear weapons!

Need: Tailored Effects

3

Range - From Stone's Throw to Global Reach

- Anywhere in the world within minutes
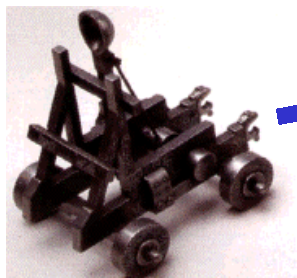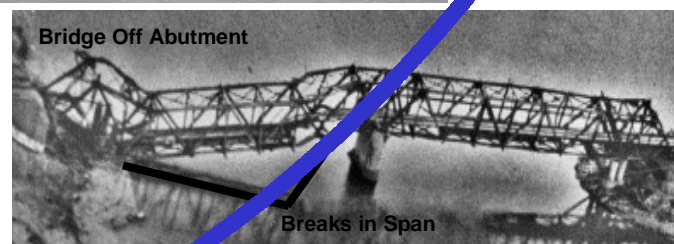- Too expensive to use on grand scale

Need: Range with mass

Precision - Long Distance but Within Feet

- Strike at fixed sites
  - within feet
  - around the world

Bridge Off Abutment

Breaks in Span

Need: Autonomy

Growing Capability - Weapon Autonomy

- Autonomous weapons now significant in battle
- Severely limited by mission planning, command, and control

Objectives in Combat

- Old ways are a constant threat

Destroying Militaries   Destroying Societies

- -

<u>Nuclear Era</u>

- Threat of escalation - new enemy is war itself!

- Need for Military Operations Other Than War

  – Peacekeeping

  – Relief in dangerous areas

  – ...

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Significant New Capability

Existing Capability +

Small size +

Autonomy +

Command/Control =

- Global reach
- Precision
- Mass
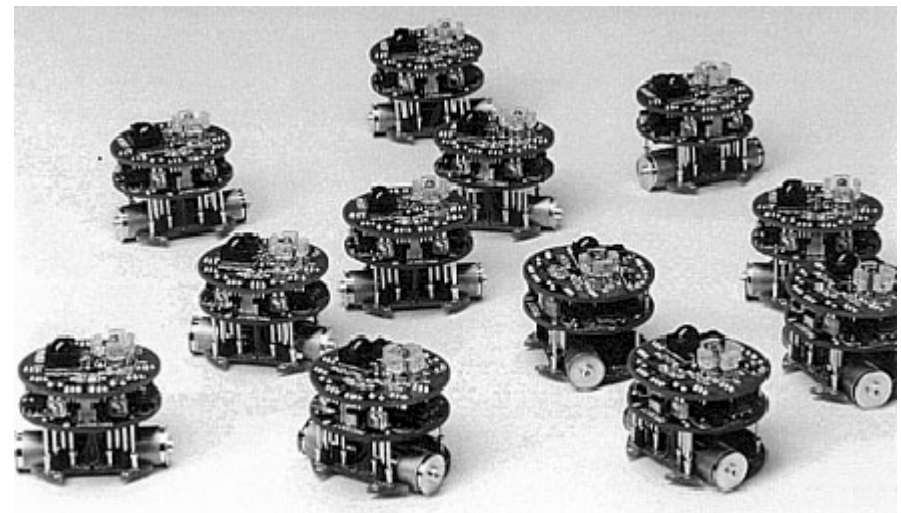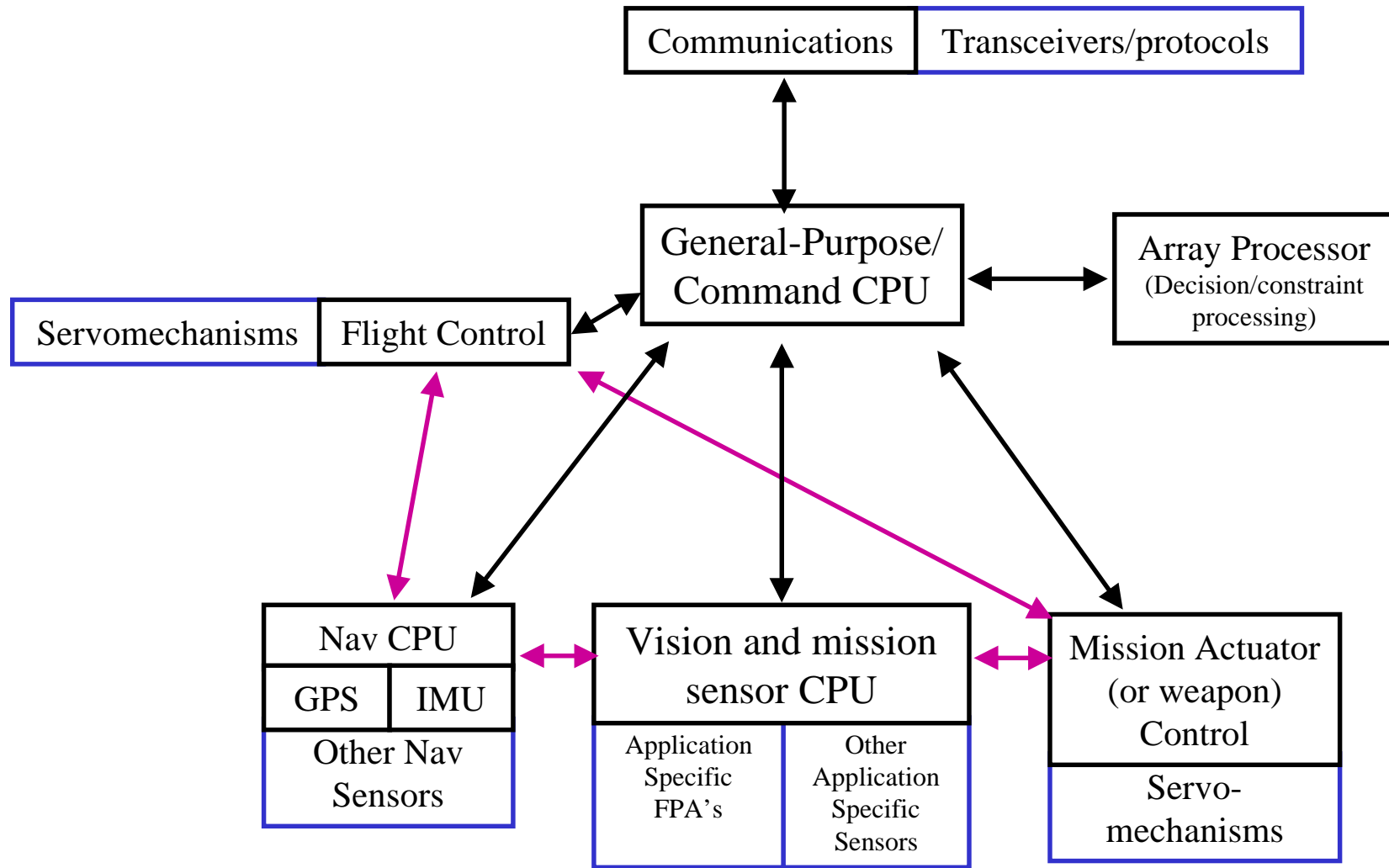- Deterrent on a continuous scale

Tension ←——————————————————————→ Major War

"Battle Bugs" -- Small Size, Autonomy

- Can be deployed in mass

- Have mass effects

- Not necessarily force-on-force

Common functions for unmanned craft can come in small packages

Communications	Transceivers/protocols

General-Purpose/ Command CPU

Array Processor (Decision/constraint processing)

Servomechanisms	Flight Control

Nav CPU		
GPS	IMU	
Other Nav Sensors		

Vision and mission sensor CPU	
Application Specific FPA's	Other Application Specific Sensors

Mission Actuator (or weapon) Control
Servo- mechanisms

Small Lethal UAV "RENEGADE"
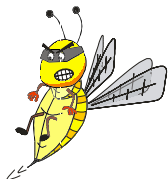
Small Killer RENEGADE UAV's dropped from larger platform
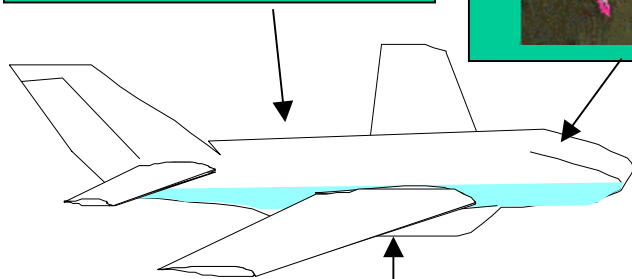
Battle is controlled by stand-off aircrew or distant command center

- Addresses difficult targets
  - Urban
  - Targets Under Trees (TUT)
  - Time-Critical Targets (TCT's)
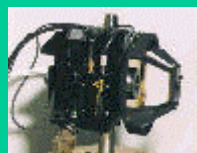- Small agile craft gets up-close and personal with the target

Computer that Sees

Agile Air Vehicle

- RENEGADE's autonomously locate, ID, and attack

- Work in swarms

Sharp-eyed, All-weather

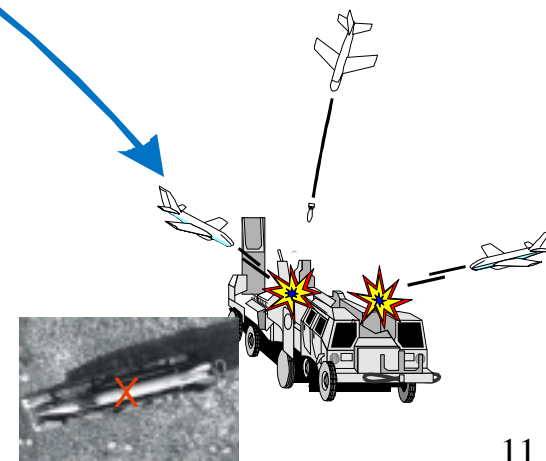- 2D-3D Optical - good images up close

- 2D-3D Millimeter Wave - images through clouds

Multipurpose weapon types
- Precision, vibration stabilized gun   - or -
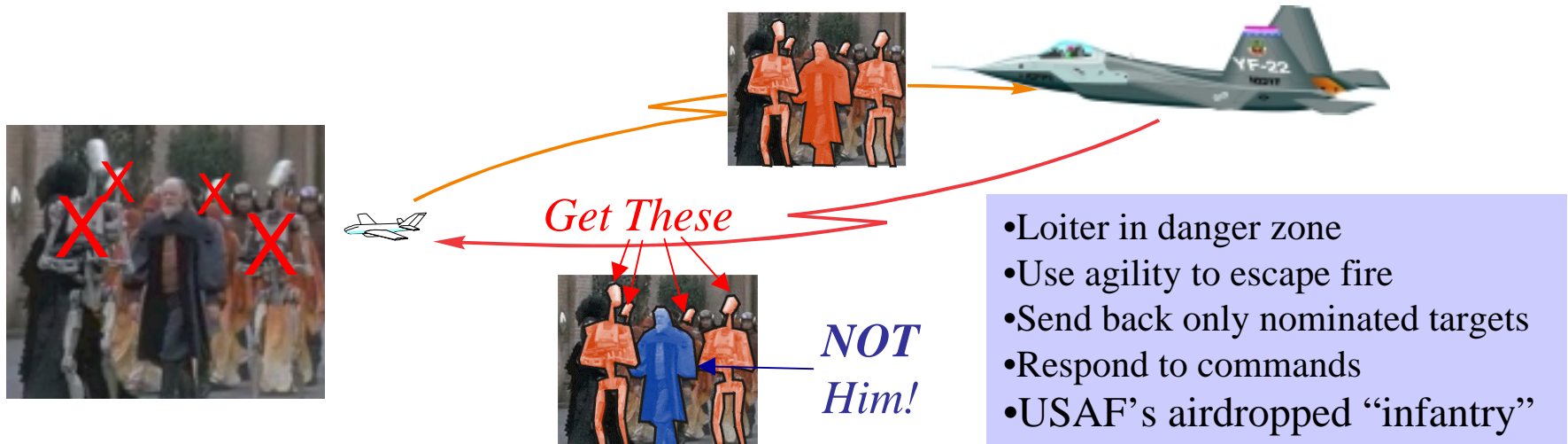- Programmable warhead (projectile or fragment)

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RENEGADE has 4 Operational Modes

- Joystick command mode

- Preprogrammed mode - similar to cruise missile

- "Search and Destroy" - like LOCAAS only smarter

- "Semi-automatic nominate-pick-shoot"
  - Nominates hard-to-find targets (e.g. Terrorists among hostages)
  - Awaits warfighter command

Get These

NOT Him!

- Loiter in danger zone
- Use agility to escape fire
- Send back only nominated targets
- Respond to commands
- USAF's airdropped "infantry"

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VIGILANTE History

APS camera

QWIP camera

UV camera

Revolutionary sugar-cube-sized processor (3DANN-R) capable of 10^{12} ops

Vigilante Target Vehicle

Low-cost, easy-to-transport air platform and ground control station for VIGILANTE

Task Purpose/Objectives: To demonstrate next-generation sensors/processors for BMDO applications

Major Products: 1) Portable, low-cost sensing/processing testbed (vib-stabilized optical bench w/ IR, vis, and UV sensors, flight platform, target vehicle, and command/control station), 2) Unique processing architecture based on tera-OPS image convolution engine (3DANN-R)

Sponsor: BMDO

Resources: (FY'00)

FY Total W/F Req'd:	7.5 WY
FY Total $ Req'd:	$1,370K
Period of Performance:	7/96 - 12/00
Total Contract Value:	$12,000K

Customer Relevance: Tool for embedded weapon system automatic target recognition problems
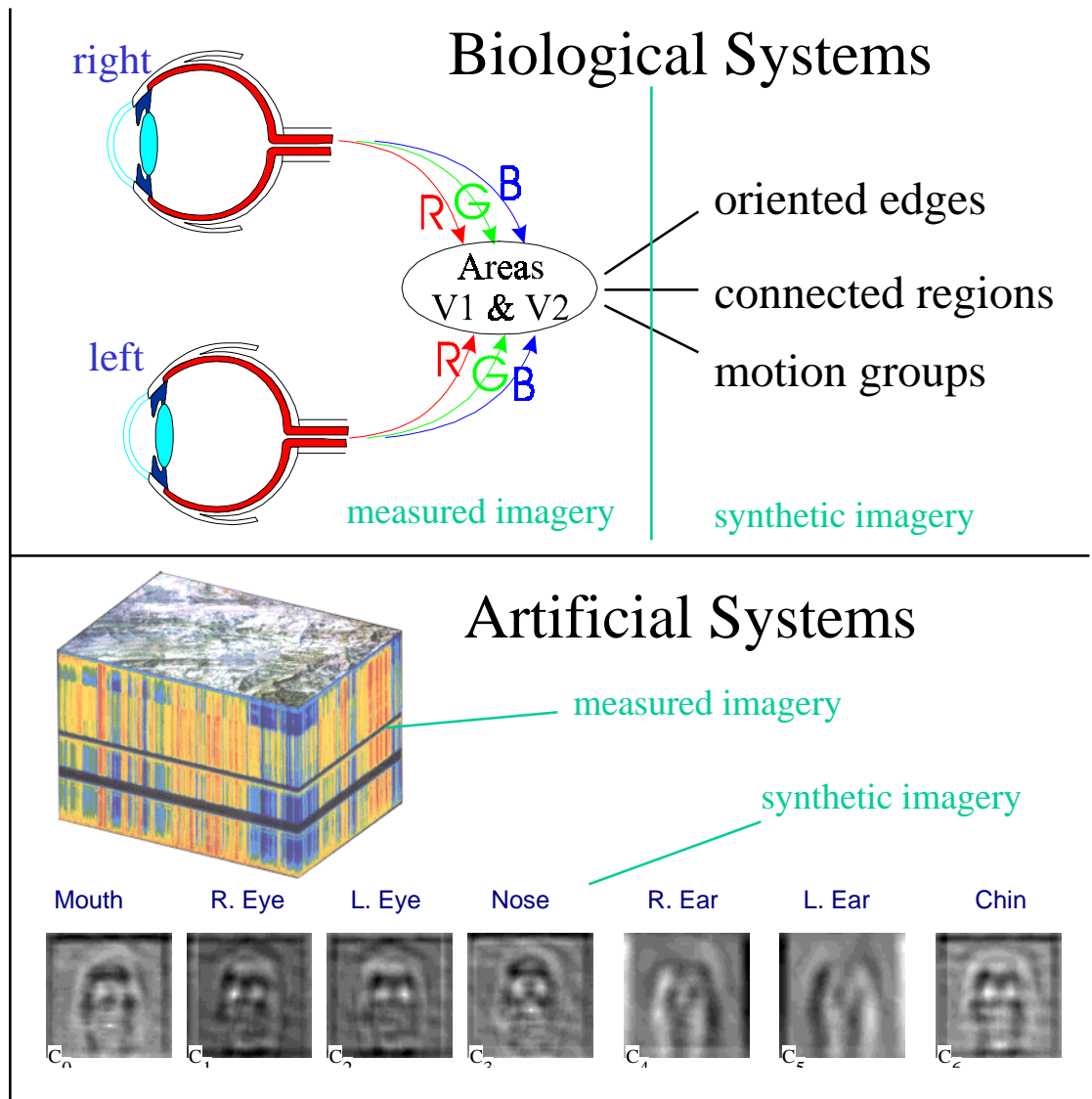
NASA Relevance: Breakthrough technology for low-mass, low-power image interpretation devices needed to enable autonomous spacecraft/robots

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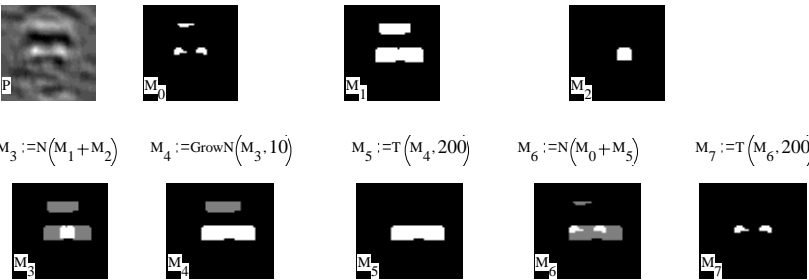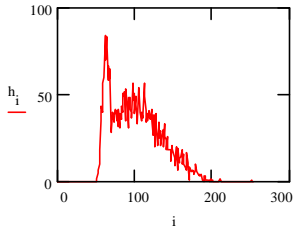# VIGILANTE fuses multiple images comparable to the eye-brain
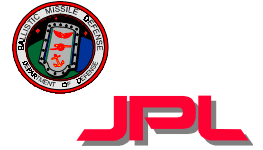
- # Real images
  - – Wavelength
  - – Stereo pairs
- # Synthetic imagery
  - – Correspondence
  - – Shape
  - – Motion fields

right

Biological Systems

B
R G

Areas
V1 & V2

oriented edges

connected regions

left

R G B

motion groups

measured imagery | synthetic imagery

Artificial Systems

measured imagery

synthetic imagery

| Mouth | R. Eye | L. Eye | Nose | R. Ear | L. Ear | Chin |

ANTE delivers unprecedented ATR speed because it has a natural data flow

$$C_k := \text{Convolve}\left(ap, Kn_k, 1, 1\right)$$
$$C_k := \text{Normalize}\left(C_k, 0, 255\right)$$

$$P := N\left(C_1 + C_2\right) \quad M_0 := T(P, 180) \quad M_1 := MD\left[M_0, 3, \begin{pmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{pmatrix}\right] \quad M_2 := ME\left[M_1, 10, (1\ 1\ 1)\right]$$

$$M_3 := N\left(M_1 + M_2\right) \quad M_4 := \text{GrowN}\left(M_3, 10\right) \quad M_5 := T\left(M_4, 200\right) \quad M_6 := N\left(M_0 + M_5\right) \quad M_7 := T\left(M_6, 200\right)$$

Type of Ops	Hardware
N^2 - image generation - convolution - gray-scale morphology - rotation/scale invariant patterns	Some custom circuits
N - image fusion "point ops" - thresholding - summing - masking	Image array processors - Princeton G.E. - WASP - CNAPS - ...
"other" - interpretation - connected component - histograms - region growing - arbitrarily connected NN's - LMS fitting	Fast serial processor (perhaps along with above processors)

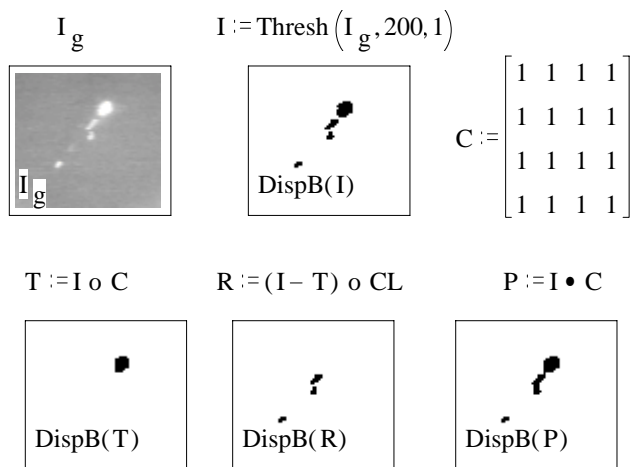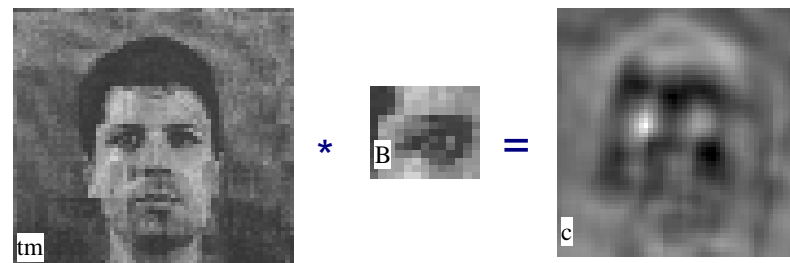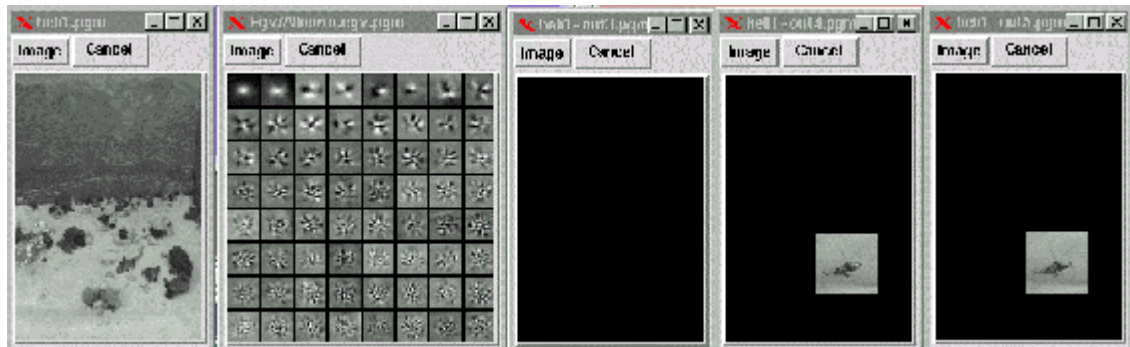# Three Basic Categories are Simplification of Basic Image Processing Taxonomy

Image Processing

Symbolic -> Image

Image -> Symbolic

Graphics

List -> Image

Image -> Image

1 -> Many

Many -> 1

Polygons
Arcs
Text
Point Draw

Point loading

Copy

1 -> 1

Histogram
Hough X-form
Blob statistics
Pixel counting
Image stats
Bounding box

Multi-Spectral

Nonlinear

Logical

Arithmetic

RGB -> HSI
"Tasseled Cap"

Rank filter
max
min"

AND
OR
XOR
XNOR
Masking
Comparison

Arctan
Average
Gradients
(angle &
magnitude)
Add
Subtract
Multiply
Divide
Absolute Diff.

Whole Image
Change Size

Whole Image
Constant Size

Local
Neighborhood

Warping
Log-polar
Linear-polar
Affine xform
Windowing
Sampling

Fourier
Hadamard

Reflection
90 deg. Rotation
Contrast stretch

Parallel
(Cellular)
Transformation

Sequential

Labelling
Distance xform
Connected components
RLE

Pixel by Pixel

Scaling
Global threshold
Bit manipulation
Table lookup

Linear

Nonlinear

Convolution
Gradient
Correlation"

Adaptive threshold
Skeletonize
Morphology
Local max

16

Unique architecture processes images at TV rates

I_g

$I := \text{Thresh}\left(I_g, 200, 1\right)$

I_g

DispB(I)

$$C := \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 \end{bmatrix}$$

$T := I \circ C$

$R := (I - T) \circ CL$

$P := I \bullet C$

DispB(T)

DispB(R)

DispB(P)

Morphology

$*$ B $=$

tm

c

Matched Filtering

Principal Component Classification
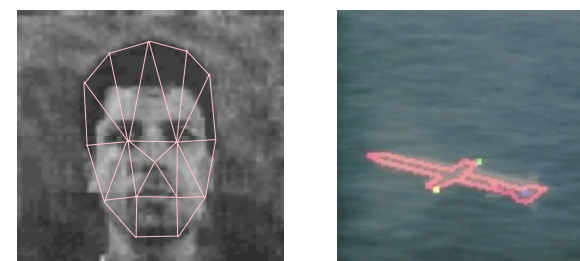
Compound Recognition and Model Matching

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3D Artificial Neural Network (3DANN) OVERVIEW

BIOLOGICAL NEURAL NETWORK

CELL BODY

DENDRITES   SYNAPSE

AXON

INPUTS

INTER CONNECTION WEIGHTS

ARTIFICIAL NETWORK MODEL

PROCESSING ELEMENT

OUTPUTS

Input to

3D Artificial Neural Network (3DANN)

64 Analog Outputs
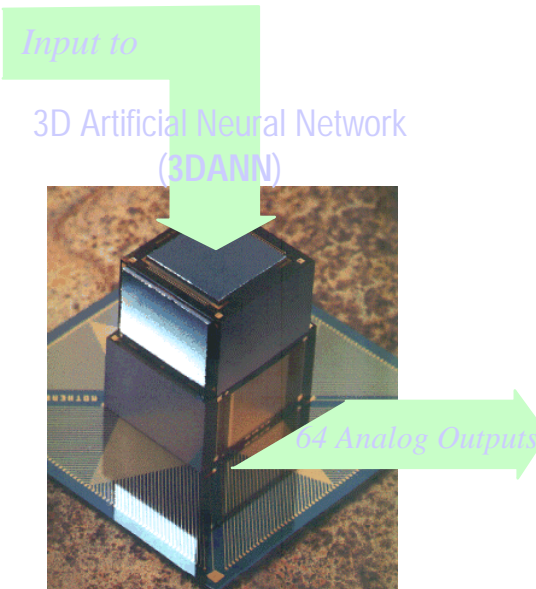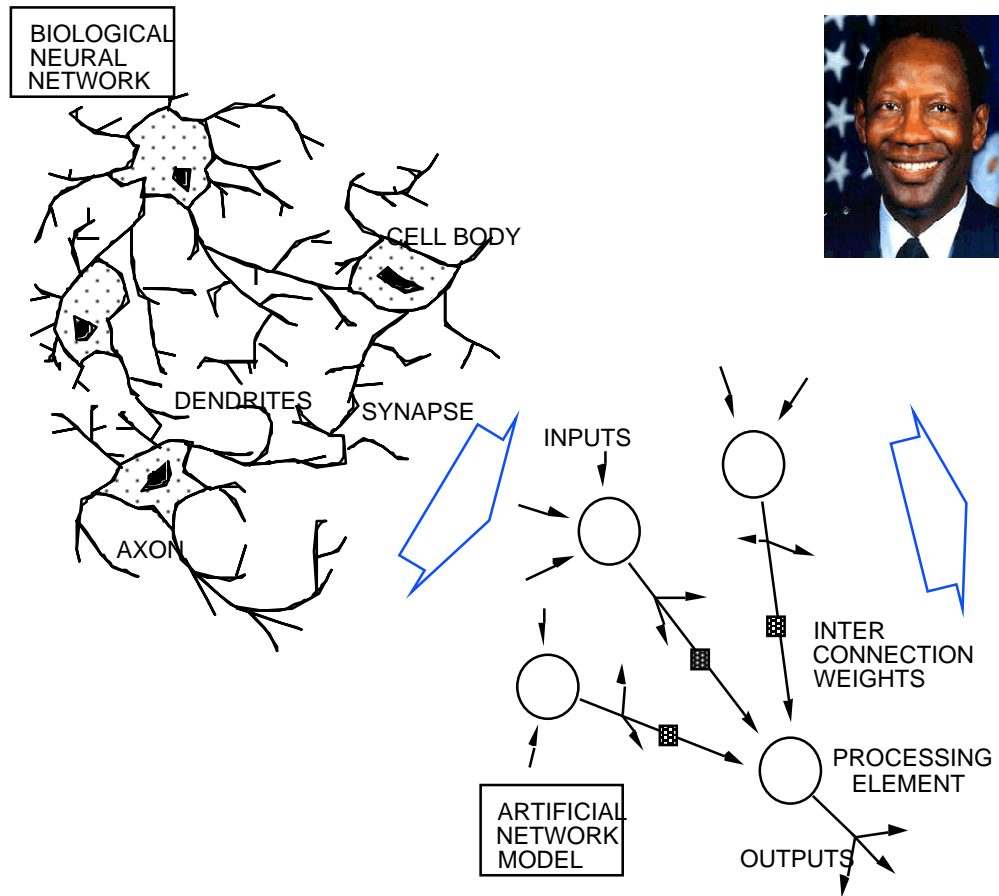
LtGen. Lyles

10 gm, 5 cc, 2 W
On-chip IR detector
1 trillion 8-bit multiplies/sec
270 million template matches/sec
Compute power greater than fast supercomputer

JPL neural network chip design enables the 3DANN technology that delivers unprecedented processing speed for ATR.

3DANN-M OVERVIEW
R
X

3DANN-Modified
Ultrafast Inner-Product/Convolution Engine

64 convolutions of 64x64 masks in 16 msec
(vs. 2 hours on state-of-the-art workstations)

3DANN NPM

256X256-PIXEL IMAGE
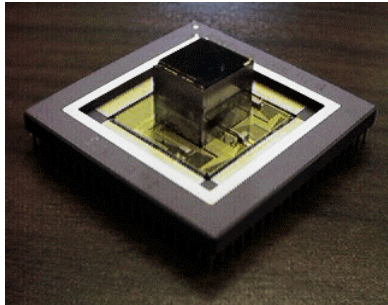
CLIC

- **AN INNOVATIVE COLUMN LOADING INPUT CHIP (CLIC) REPLACES THE 64X64-PIXEL IR SENSOR ARRAY OF 3DANN**

- **RASTERED 64X64 WINDOW OF A LARGER IMAGE FROM ANY TYPE OF SENSOR ARRAY IS FED-IN AS INPUT TO 3DANN FOR REAL TIME PROCESSING**

HIGH SPEED RASTERED IMAGE WINDOW TRANSFER FROM IMAGE BUFFER TO 3DANN
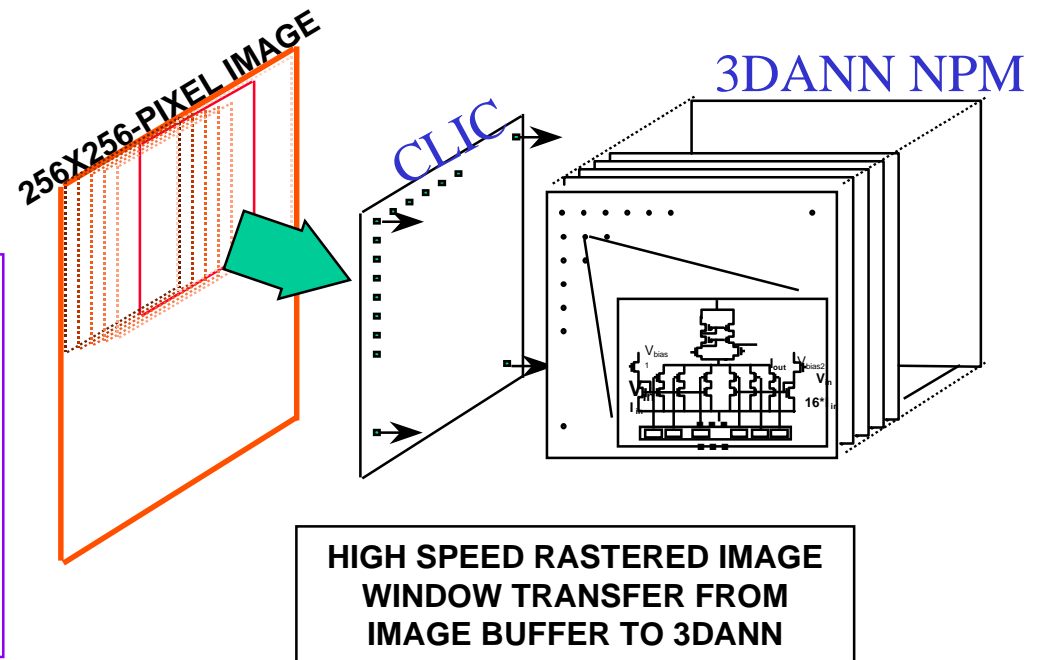
3DANN-M represents a general-purpose ATR computer capable of accepting image data acquired from any size and type of sensor array.

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3DANN-M^R Delivers Unprecedented Processing Speed for VIGILANTE

3DANN-M
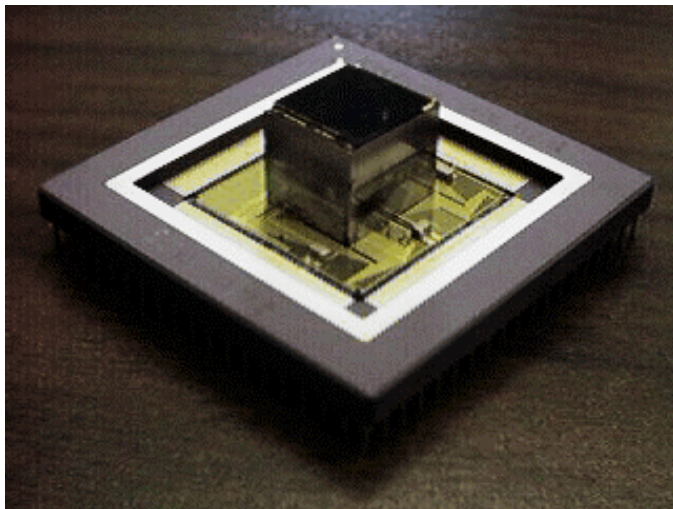
Mass = 10 gm
Volume = 5 cc
Power = 3 W
Computational power greater than fast supercomputer

VIGILANTE	Sparc 20
~16 msec	~2 hrs

Timing comparison based on convolving a 256x256 image with multiple 64x64 templates for recognition and tracking of desired features, e.g.,
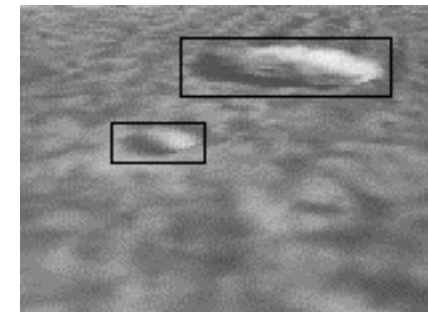
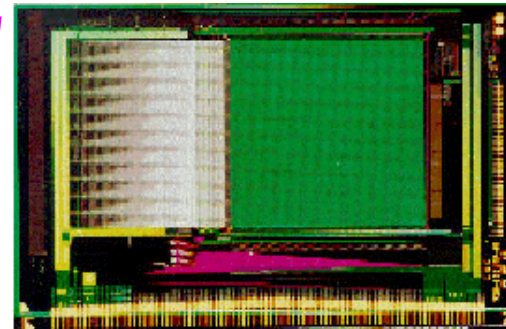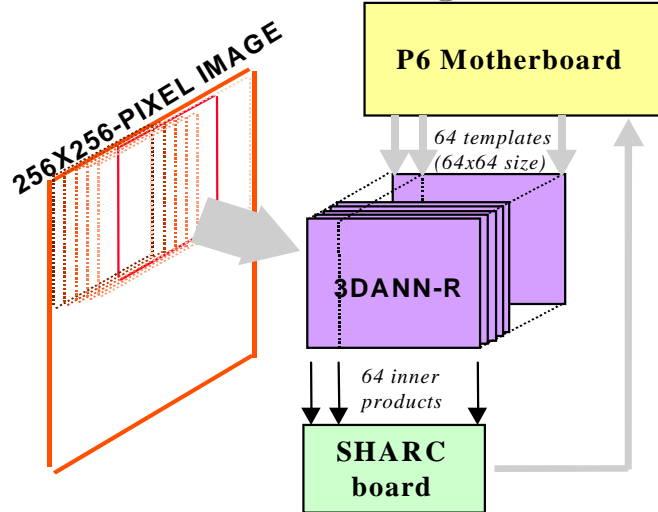Planetary feature recognition using VIGILANTE architecture.

VIGILANTE -- breakthrough technology for intelligent vision

VIGILANTE Processing Architecture

256X256-PIXEL IMAGE

P6 Motherboard

64 templates (64x64 size)

3DANN-R

64 inner products

SHARC board

3DANN-R mixed-signal ASIC using 0.6 μm CMOS and over 1 million transistors (sponsored in part by AFRL, Phillips Research Site, Contract F29601-98-C-0067)

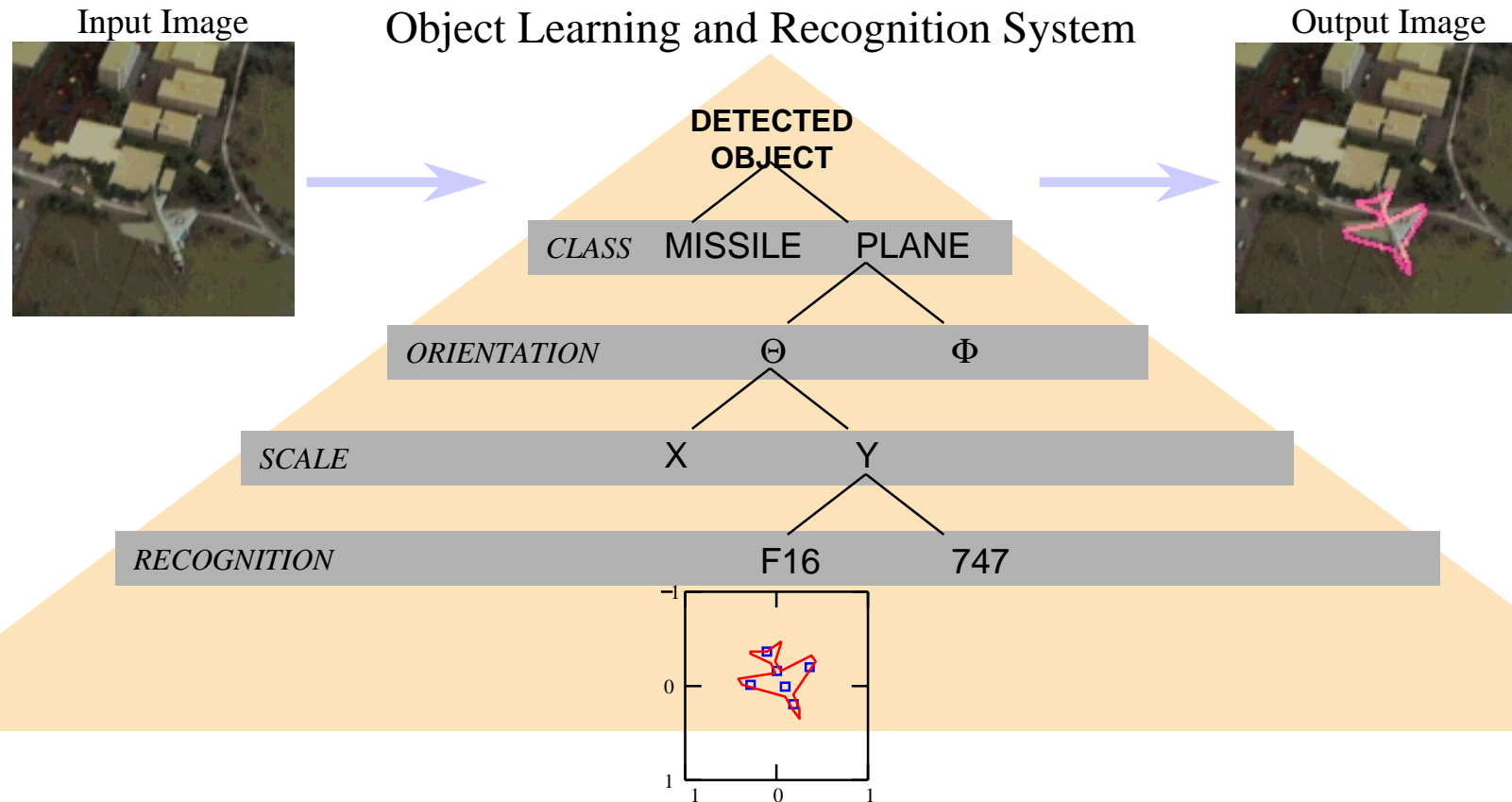***Unprecedented real-time automatic target recognition in a small package***
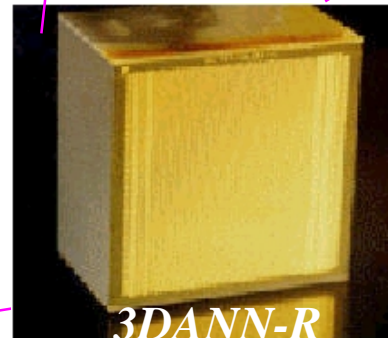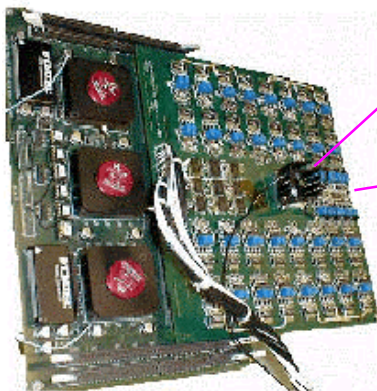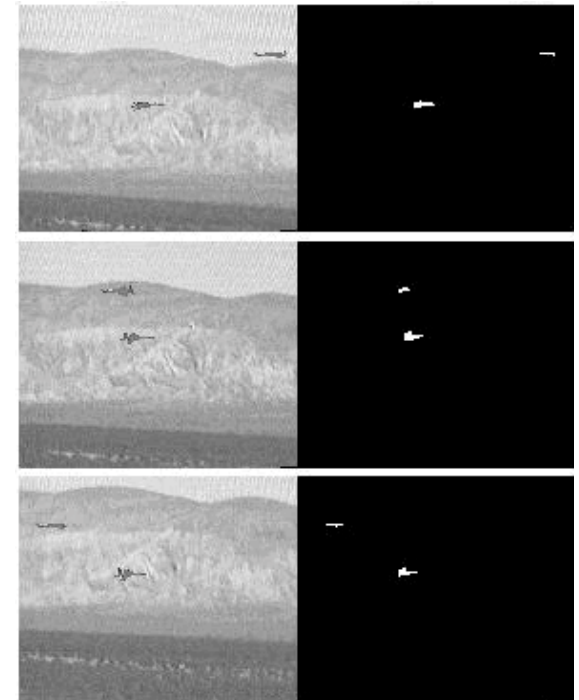
3DANN-R

3D Convolution processor, containing 64 row convolver IC's capable of 1 TeraOPS in a 1.4cm x 1.45cm x .75 cm/8W package

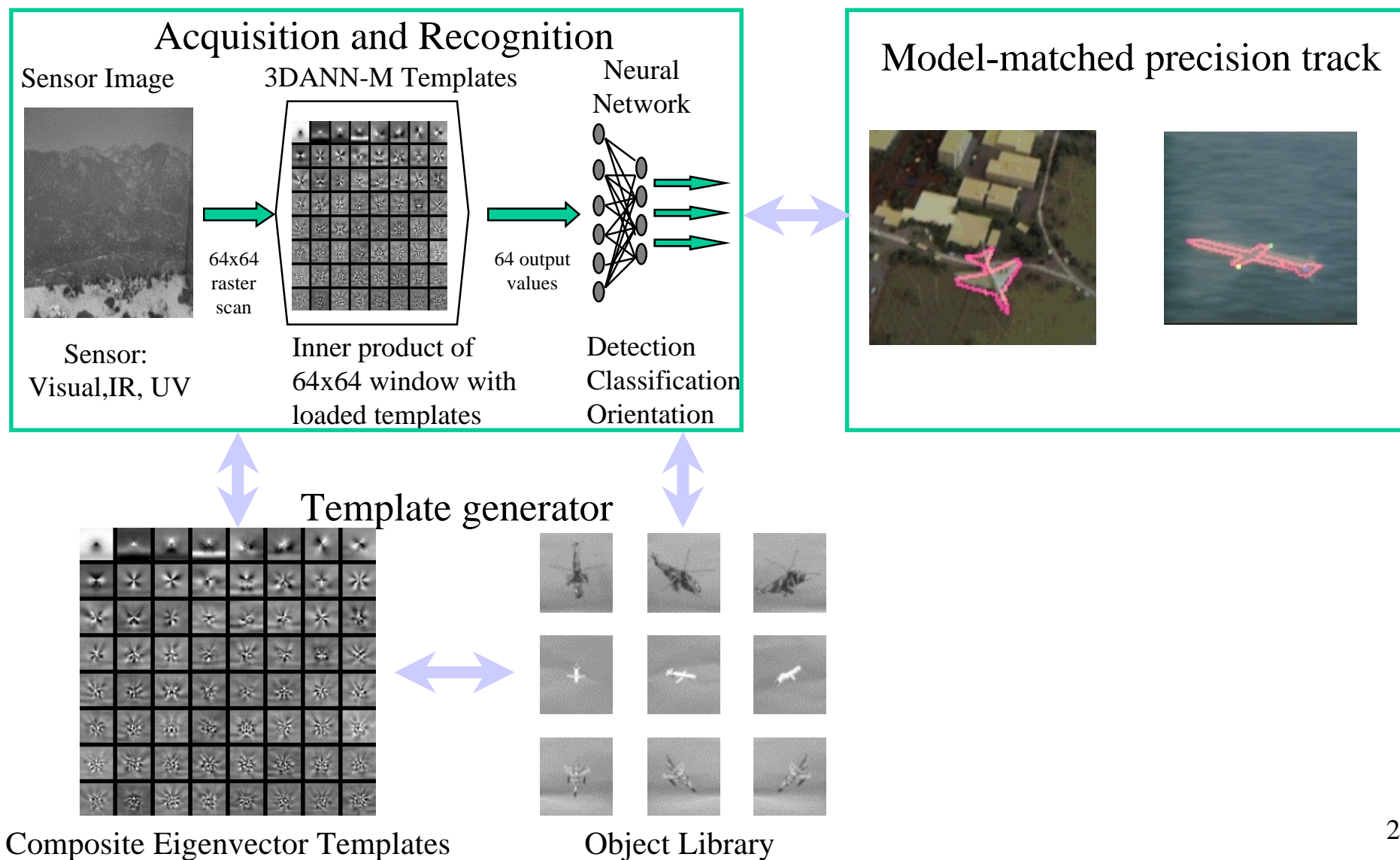*3DANN-R motherboard/daughterboard providing A/D, memory, and interface to host computer*

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VIGILANTE architecture runs parallel algorithms that successively refine detail

Input Image

Object Learning and Recognition System

Output Image

DETECTED OBJECT

CLASS   MISSILE   PLANE

ORIENTATION   Θ   Φ

SCALE   X   Y

RECOGNITION   F16   747

Hierarchical learning and recognition is the only avenue to efficiently achieve Detection through "Precision Tracking," and 3DANN-M enables the implementation of this ATR in real-time.

VIGILANTE target recognition scheme has been demonstrated piecewise in simulation/lab environments

Acquisition and Recognition

Sensor Image

3DANN-M Templates

Neural
Network

64x64
raster
scan

64 output
values

Sensor:
Visual, IR, UV

Inner product of
64x64 window with
loaded templates

Detection
Classification
Orientation

Model-matched precision track

Template generator

Composite Eigenvector Templates

Object Library

Technical Highlights

VIGILANTE has demonstrated the visual intelligence capability analogous to human brain

Input Scene

Classification Output

3DANN-R Analog Outputs that map target features based on Eigenvector templates
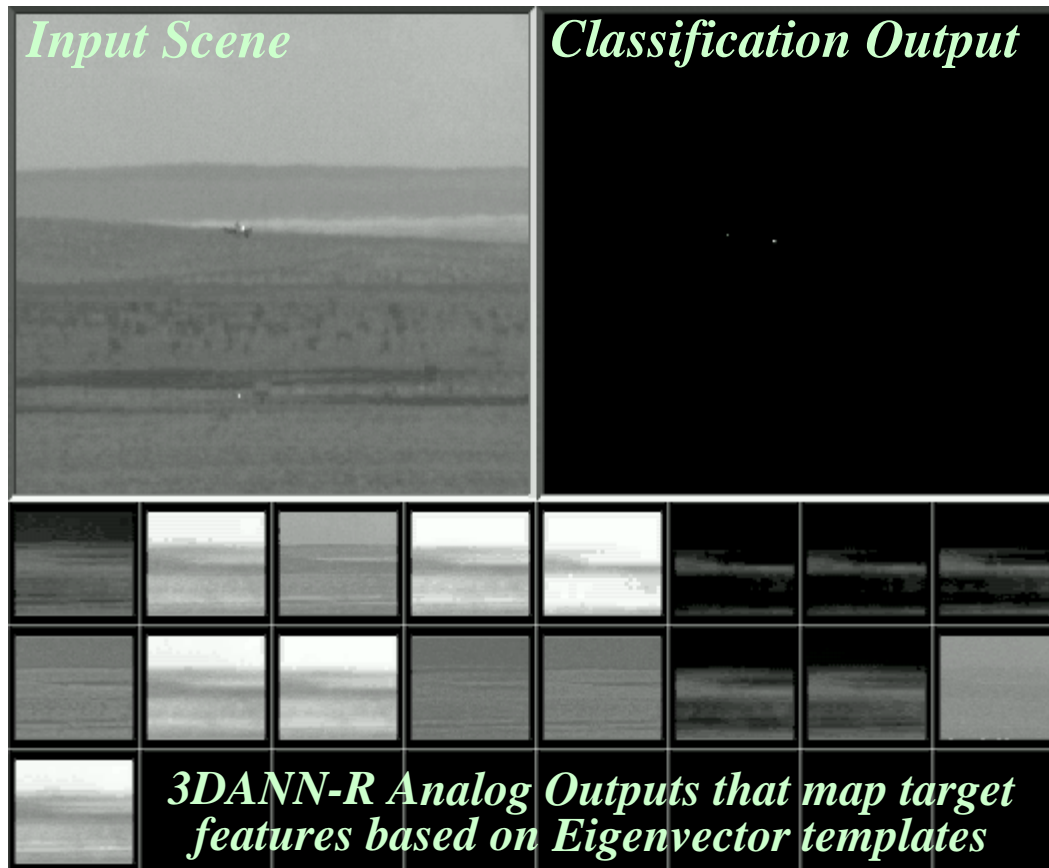
- Robust distortion-invariant (scale, orientation, and lighting) target recognition in highly cluttered background scenes

- Templates are generated from computer models based on general physical descriptions of the target

- Recognition is carried out using only 7-bits of resolution from 3DANN-R

- Functionality at 0.25 tera-ops ($\Rightarrow$8 frames/sec) has been demonstrated in the lab—mother/daughterboard rework is needed for running 3DANN-R at full speed (i.e., 1 tera-ops)

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Precision tracking matches a model to a flying target

Recognition

Input color image
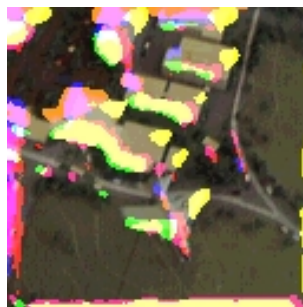
Output of thresholded convolution filters
(state of the art)

Detected features with rich pixels
(VIGILANTE will do this at frame rate!)

Model matching

Cruisew.avi

Cruise missile example
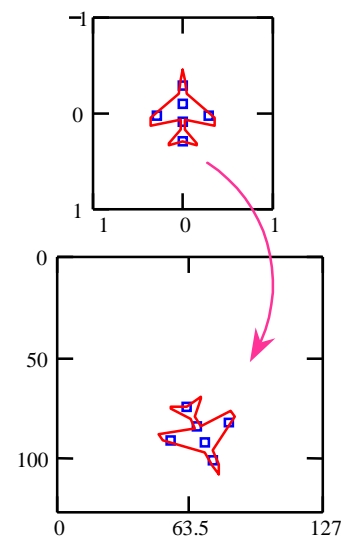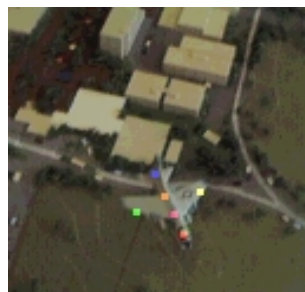
Key:
- • - Nose
- • - Right wing
- • - Left wing
- • - Tail
- • - Aft fuselage
- • - Weapons area

Computational burdens for enormous amount of data from various sensors can now be accomplished on order of milliseconds

SAR data processing in 1 msec
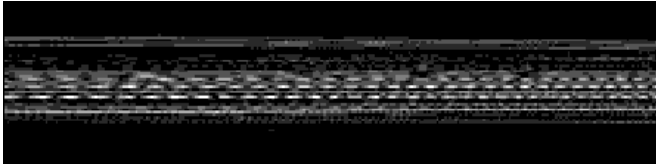
Raw data (64x256)

Processed data using FFT (~30msec on a 100MHz DSP)

Uncorrected 3DANN-R outputs

*Simultaneous machine vision computations (up to 64 transformations) in 30 msec*

Processing of a data cube structure in microseconds vs. seconds on workstations
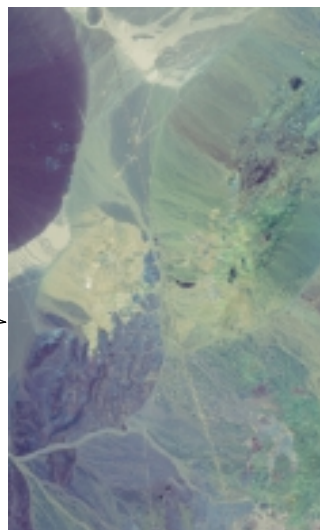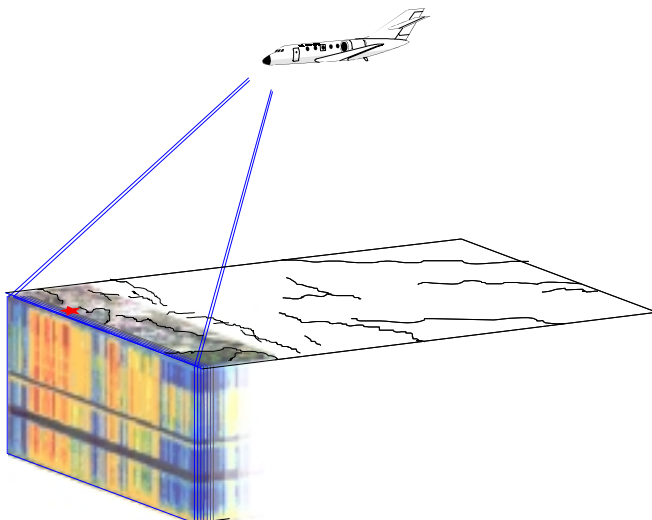
Faster and more efficient solutions to sensor fusion and target detection
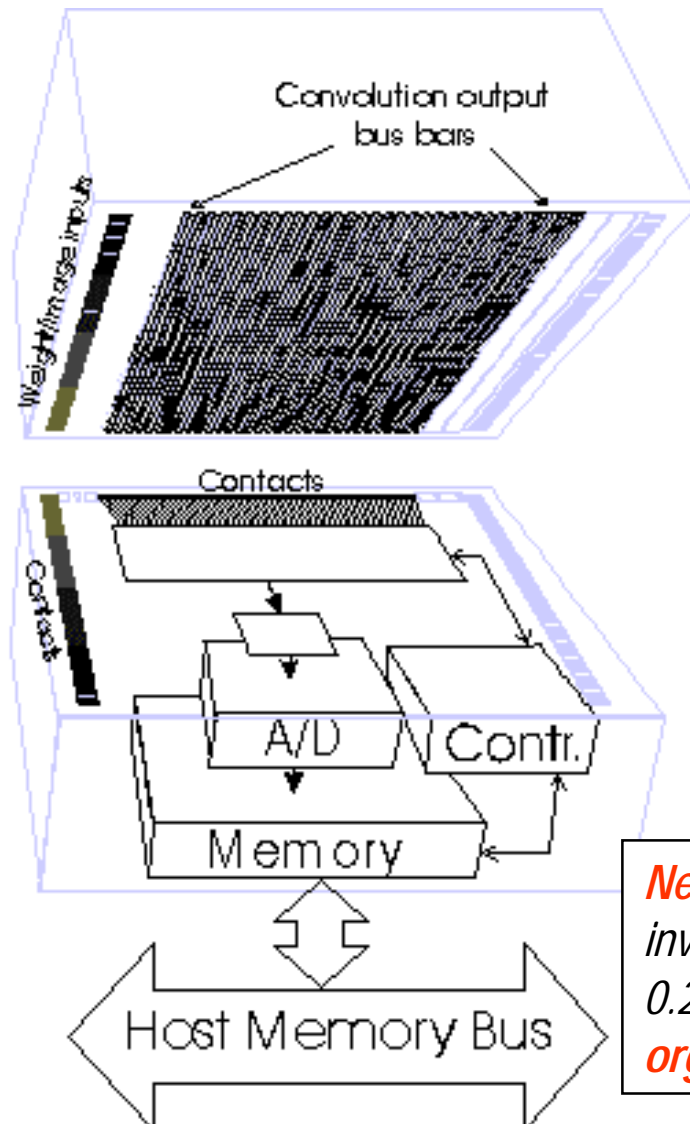

32x64

32x64

32x64

32x64

32x64
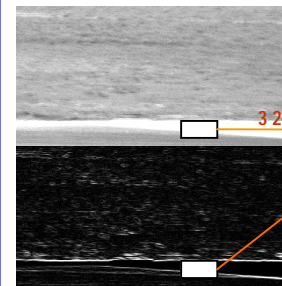
Sensor Fusion
Templates designed to enhance SNR of the target's appearance by optimizing the co-occurrence probabilities when using multiple sensors
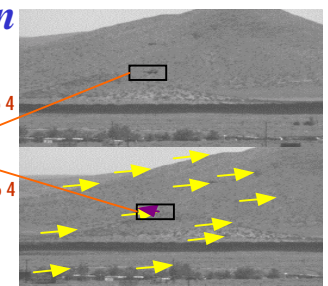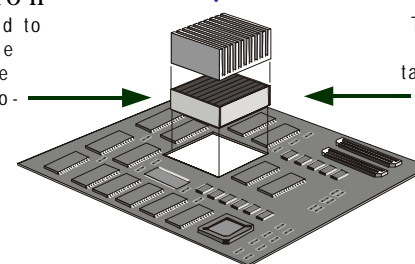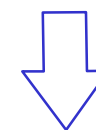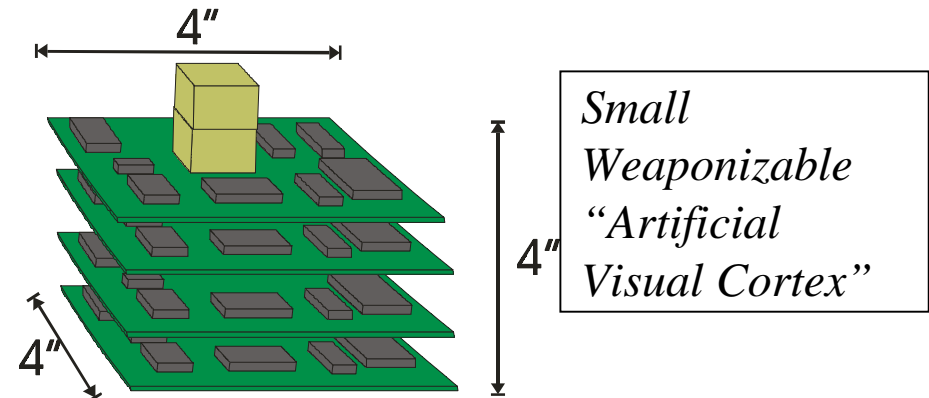
Optical Flow
Templates designed to enhance SNR of the target's motion (rotation and translation) in background by optimizing the changes with respect to these transformations

Next generation 3DANN-R is field deployable and revolutionizes war-fighting & missile defense systems
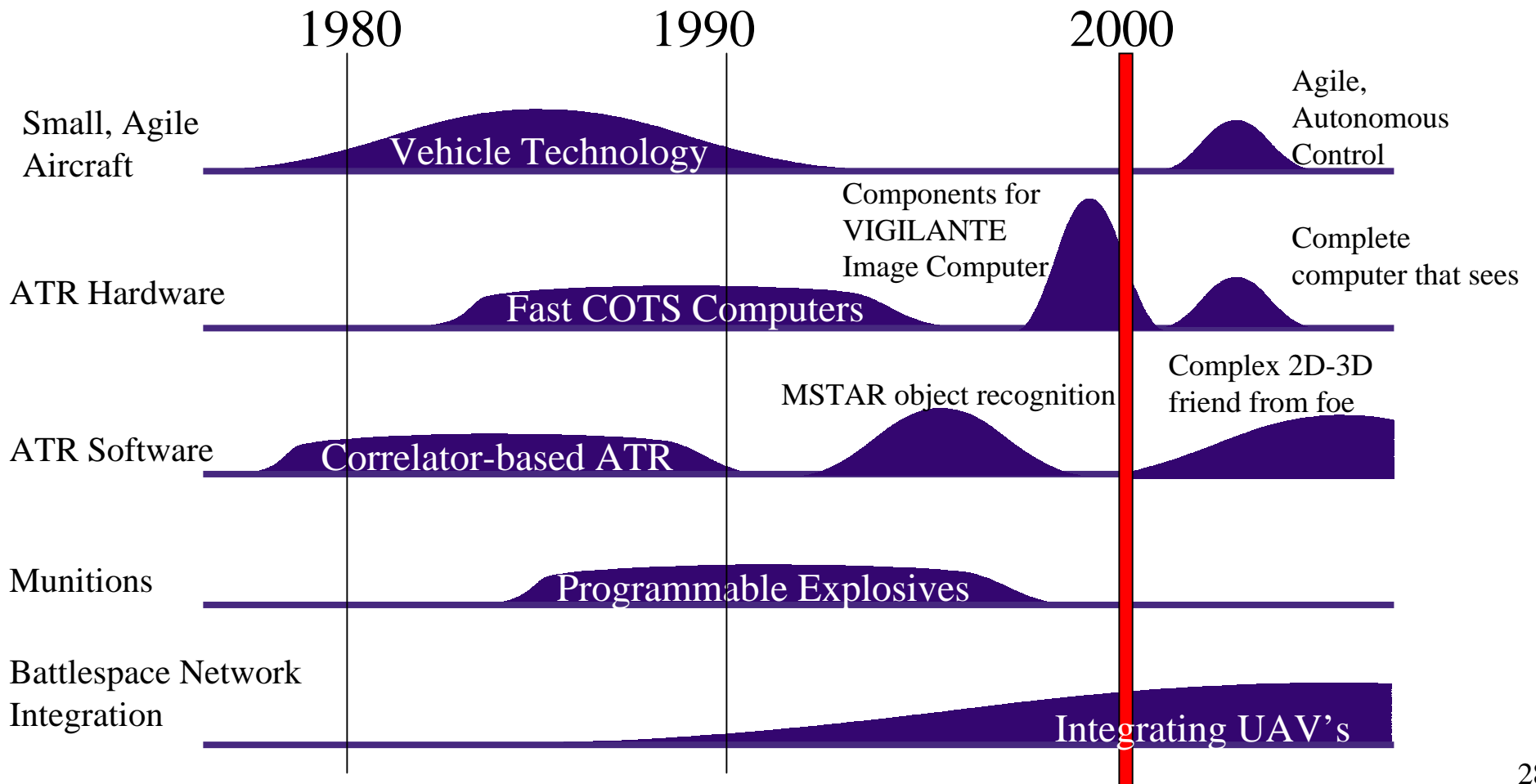
- Revolutionary "computer that sees"
- Complete system will fit into palm-sized package

4"

4"

4"

Small Weaponizable "Artificial Visual Cortex"

Convolution output bus bars

Weight/Image input

Contacts

Contact

A/D | Contr.

Memory

Host Memory Bus

Next generation 3DANN-R: Two mated 3D stacks involving MEMS, heterojunction devices, and 0.1-0.2μm CMOS *to realize an intelligent image organizer/interpreter with 30+ TeraOPS capability.*

# Many Technology Barriers Crossed -- Others Remain

| | 1980 | 1990 | 2000 | |

Small, Agile Aircraft
Vehicle Technology
Agile, Autonomous Control

ATR Hardware
Fast COTS Computers
Components for VIGILANTE Image Computer
Complete computer that sees

ATR Software
Correlator-based ATR
MSTAR object recognition
Complex 2D-3D friend from foe

Munitions
Programmable Explosives

Battlespace Network Integration
Integrating UAV's
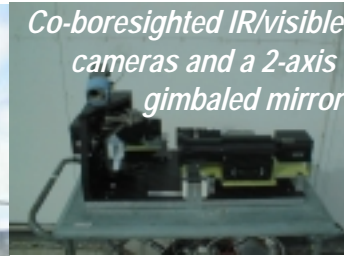
RENEGADE levels of prototyping

1. *Concept* only -- "Viewgraph"

2. Develop *components*/Simulate system

3. Test system concept via *remote* links

4. Develop complete *prototypes*
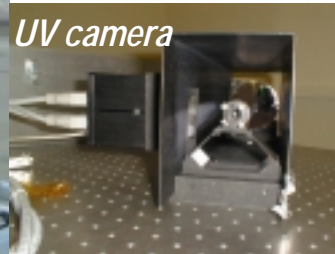
5. Develop *operational*/production prototype

VIGIL is the data collection and ATR demonstration platform

Co-boresighted IR/visible cameras and a 2-axis gimbaled mirror
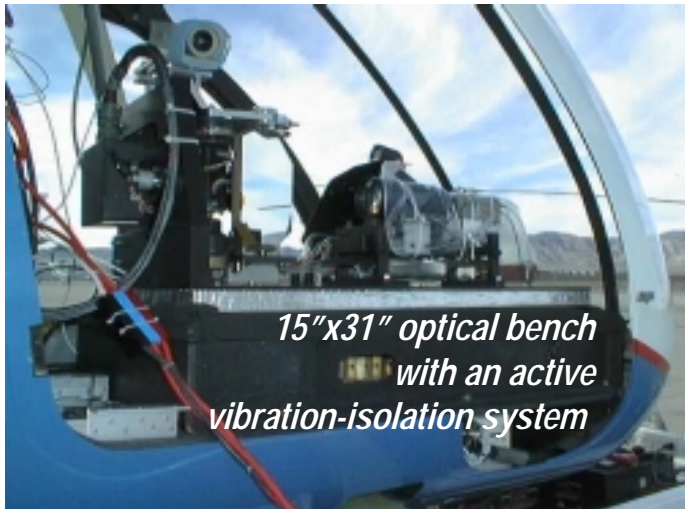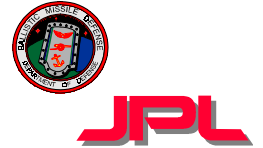
15"x31" optical bench with an active vibration-isolation system

UV camera

GPS mounting on ATI helo
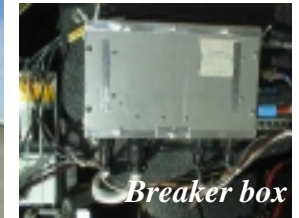
Breaker box

Vibration isolation system

IMU

Attitude GPS computer & comm. router

Ground Control Station

Monitors

VCR

VIGIL PC

VTV PC
GCU

GCU: 486PC104, GPS, and 2 radio modems

Flight experiments conducted at National Test Pilot School, Mojave, CA

• National Test Pilot School and Flight research Inc. are commercial flight test and training operations.

• Maintain and instrument experimental R&D aircraft.

• 20 years experience.

• NTPS has a joint use agreement with the US Air Force at Edwards AFB and the US Navy at China Lake to use restricted range areas.

• NTPS has at their disposal three runways, modern control tower, fire station and medivac.

• Self contained flight operations center.

Data collection used various VTV options
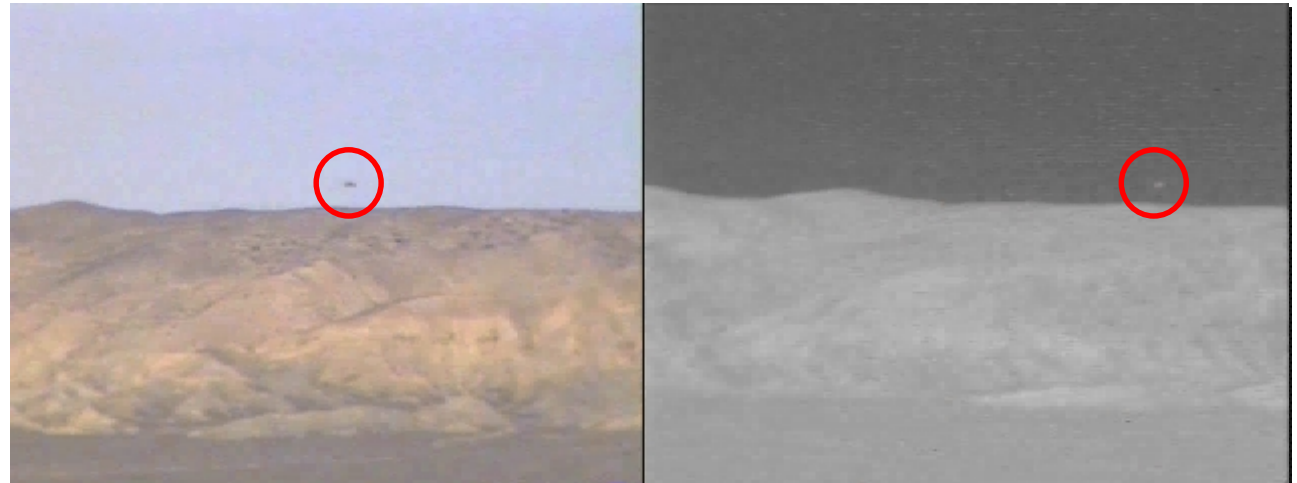
Temporary VTV#1

Temporary VTV#2

VTV#1

VTV#2

Flight test results

Temporary VTV#1

Temporary VTV#2